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Protection in elastic optical networks using Failure-Independent Path Protecting p-cycles

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ABSTRACT

This paper presents heuristics based on FIPP p-cycle as a solution for the protection problem in elastic optical networks. The proposed algorithms employ failure independent path protecting p-cycle (FIPP). The algorithms differ by the protection of either one or two simultaneous failure as well as by the employment of traffic grooming and spectrum overlap. An integer linear programming (ILP) is formulated and results compared to those given by the heuristics. Results given by the heuristics are close to those given by the ILP.

1. Introduction

Advances in communication networks and the flexibility of the Internet application layer have allowed the emergence and rapid spread of numerous services and applications which have shaped the way we live and communicate. However, such networks must always be available, since disruption of communication services significantly impacts on our daily life. The ability of a network to maintain acceptable levels of service in the face of unavailability of any of its parts (resilience) is a crucial aspect in designing communication networks.

The evolution of such networks has mostly been supported by optical network technology and has been the primary technology for the data link layer of the Internet backbone. This technology has played an essential role in meeting the growing demands for bandwidth. The capacity of this layer increased due to the use of the wavelength division multiplexing (WDM) technology which allows multiplexing of several wavelengths (optical channels) in a single fiber link. In WDM links, the optical spectrum is divided into frequency slots of a fixed width of either 50 GHz or 100 GHz, allowing the use of up to 80 and 40 optical channels, respectively. The use of advanced modulation techniques in optical transmission systems has made available rates greater than 100 Gbps per optical channel. However, this rigid frequency grid becomes a barrier to optical transmissions at higher rates, e.g. 400 Gpbs and 1000 Gbps, which demand frequency slots larger than 100 GHz. On the other hand, optical transmission at low rates requiring less than 50 GHz leads to inefficient use of the optical spectrum. This inefficiency has motivated the adoption of a less rigid division of the spectrum in the so-called elastic optical networks, which can accommodate diverse bandwidth demands. In these elastic networks, the spectrum is also divided but into smaller fixed 12.5 GHz slots, thus allowing the allocation of the spectrum with a much finer granularity. The number of slots allocated can thus provide a better match for a requested bit rate, avoiding the spectrum waste in WDM networks.

Given the enormous capacity of each optical fiber, the disruption of any of them implies a massive loss of data; previous papers have investigated the protection of the paths in these elastic optical networks [1–6]. Their vulnerability has motivated the development of various protection and restoration schemes, with p-cycle being one attractive option [7–9]. Given that p-cycles are shared protection rings they protect the working capacity on the span they cover, but unlike rings, they also protect the working capacity of the off-cycle spans with end-points on the p-cycle ("straddling spans"). They thus combine the ring-like recovery speed with the efficiency of restorable mesh networks. One special p-cycle is the Failure-Independent Path Protecting p-cycle (FIPP p-cycles) which provides fully pre-connected protection paths; however, the design of networks employing p-cycles is complicated by the computational complexity of the problem, which grows exponentially with the number of nodes and the number of links. Since network design using p-cycle is an NP-hard problem, various heuristics algorithms have been developed to solve it [10].

This paper addresses the path protection problem in elastic optical networks by presenting several algorithms based on Failure-Independent Path Protecting p-cycle. The FIPP-Flex algorithm protects networks against a single failure, and the FIPP-Flex-twofailure makes use of straddling p-cycle properties to protect networks against two simultaneous failures. A third algorithm, the FIPPSh-Flex algorithm, extends the

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FIPP-Flex algorithm to allow traffic grooming as well as spectrum overlap between disjoint backup paths; all the proposed algorithm employ a routing and spectrum assignment algorithm based on a multigraph representation of the spectrum. Moreover, results produced by these algorithms are compared to those given by an Integer Linear Programing (ILP) model to evaluate their accuracy. Despite the large capacity required for the provision of pre-connected 100% guarantee path protection, the numerical results indicate that the proposed algorithms are worth adopting in networks with high node connectivity.

This paper differs from our previous conference papers [5,6,11] by redefining the proposed algorithm, by providing for the joint evaluation of the algorithms using a variety of scenarios and by comparing them with other existing algorithms.

This paper is organized as follows. Section 2 reviews related work. Section 3 introduces the concept of p-cycle, while Section 4 reviews the concepts of traffic grooming in EONS and spectrum overlap. Section 5 introduces an ILP to derive backup paths in optical networks using FIPP p-cycles. Section 6 establishes the network model used in the paper. Section 7 introduces the RSA-FLEX algorithm which serves as the basis for the algorithms in this paper. Section 8 presents the algorithms FIPP-FLEX, FIPP-FLEX- twofailure and FIPPSh-FLEX. Section 9 evaluates the performance of the proposed algorithms and Section 10 concludes the paper.

2. Related work

Several papers for routing and spectrum allocation for elastic optical networks have addressed the protection of these networks [1–6,10, 12–21].

In Refs. [17,18], the authors compared the p-cycle network protection technique with the ring cover technique for the protection of elastic optical networks. Chen et al. [19] developed a theoretical model to precisely analyze the service availability of networks with p-cycles. Ji et al. [20] studied p-cycles with Hamiltonian cycles and proposed the use of topology partition for reducing the length of backup paths. Wu et al. [21] proposed a new heuristic algorithm using p-cycle considering the single-fiber link failure. The authors considered load balancing and criteria for choosing the proper working path for each demand. However, they considered only link protection and not path protection.

In Jino et al. [12], the authors presented elastic and adaptive optical networks and scenarios from rigid optical networks to elastic and adaptive optical networks. Zhang et al. [13] proposed a novel optical grooming approach to aggregate and distribute traffic on the optical layer in OFDM-based elastic optical networks. These authors studied routing and spectrum allocation algorithms and employed traffic grooming to show the benefits of this approach. The authors in Ref. [3] proposed survivable transparent flexible optical WDM (FWDM) and studied the survivability of elastic optical networks with traffic grooming. They proposed the use of the First-Fit policy to assign spectrum to the working paths, and the Last-Fit policy to assign spectrum to the backup paths.

Shao et al. [1] have proposed a scheme in which backup lightpaths with different allocated capacities can protect working lightpaths with disjoint paths, thus leading to more efficient use of resources to provide path protection. Liu et al. [2] proposed a new technique for shared protection which shares the spectrum of a backup path with other backup paths that have disjoint working paths. This protection approach is called elastic separate- protection-connection (ESPAC).

In Ref. [10], the authors presented the concept and the advantages of FIPP p-cycle algorithms and in Ref. [14] the same authors developed an ILP model for FIPP protection with much faster execution times. In Ref. [15], the authors apply the p-cycle design for a single link failure, as well for as a single Shared Risk Link Groups (SRLG) failure. They introduce an integer linear programming (ILP) formulation that minimizes the spare capacity. In Ref. [16], the authors present a p-cycle based method to deal with dynamic traffic in the survivable WDM network and they compare the performance of the p-cycle based design using various routing strategies to that of shared backup path protection (SBPP).

In Ref. [22], the authors reviewed routing and spectrum allocation algorithms and routing, modulation and spectrum allocation algorithms proposed for EON. They analyzed and compared their performance and computational complexity. Alyatama et al. [23] proposed an adaptive routing and spectrum allocation algorithm for elastic optical networks which relies on the history of carried calls to learn the near-optimal searching sequence of the optical spectrum. In Ref. [24], the authors extended the p-cycle by allowing cycles to have attached links, called Parasitic Protection Links (PPL), in order to protect paths which source and destination nodes are located on the cycle and connected by a PPL. A p-cycle with PPL is named p^2 -cycle. Walkowiak et al. [25] formulated an RSA algorithm with dedicated path protection as an Integer Linear Programming (ILP) problem. They developed a Tabu Search-based algorithm (TS) and a hybrid Adaptive Frequency Assignment- TS (AFA/TS) algorithm for the RSA problem.

3. p-Cycle

Protection involves the use of pre-configured schemes in which resources are reserved for the recovery from failures, whereas restoration refers to the dynamic recovery of a network and its services when a failure occurs. If, on the one hand, protection can guarantee 100% protection against failure, on the other hand, it does not efficiently use the network capacity. It is, thus, preferable to employ path protection rather than restoration since it may not guarantee 100% recovery from failure if there is no available backup path at the time of the occurrence of the failure. In path protection, the working (primary) path designates the traffic carried operationally while a secondary (backup) path provides an additional path to carry the traffic in the event of failure. Two types of path protection are common: dedicated path protection which utilizes two non-disjoint protection paths employing different spectrum bands (wavelength), regardless of the disjointedness of the working paths, and shared path protection in which spectrum bands are shared.

The use of p-cycle provides a protective scheme in which spare capacity is pre-connected to form ring-like structures, the so called p-cycles [7]. These p-cycles provide Bi-directional Line Switching Ring (BLSR) protection considered to be a generalization of the 1:1 protection scheme [8]. The main difference from conventional ring protection is that p-cycles provide two protective paths for each link that straddles the cycle, thus protecting more connections. The straddling links have working capacity, but no spare capacity [26]. Moreover, working paths can be freely routed over a mesh structure which is not restricted by a ring-constrained routing topology. In networks protected by p-cycles, however, in the event of failure, only two switching actions at the end nodes of the failed span are necessary to switch the traffic to a protective path, as in a conventional ring, thus providing rapid restoration not because rings are involved but because they are path fully pre-connected before the occurrence of the failure [9].

A particular case of p-cycle for path protection is the so-called Failure-Independent Path Protecting p-cycles (FIPP) [27]. FIPP p-cycles furnish protection to end-to-end working (primary) paths with end nodes on the p-cycle. FIPP is an extension of the p-cycle concept, FIPP is based on the disjointness of working and backup paths, and provides independence of fault detection in relation to the location of the fault, thus results in failure independence. Failure independence is quite advantageous when the localization of a fault is slow or difficult, such as in transparent or translucent networks. This is an advantage over traditional path protection schemes, as well as over flow p-cycles.

Shared-Backup Path Protection (SBPP) was proposed for networks based on IP signaling; it is also failure independent. However, it differs from FIPP since in SBPP the backup path needs to be determined on the fly upon the occurrence of a failure, and a restoration path with poor transmission quality may be chosen. Thus, the pre-connection of a protective path is essential to assure the quality of transmission. The combination of failure independence and pre-connected protection paths in

FIPP p-cycles leads to ring-like protection with minimal real time restoration of a path, as well as minimal signaling overhead.

4. Traffic grooming in EONs

In optical networks, traffic grooming combines multiple connections in a single lightpath [13]. In WDM networks, traffic grooming merges low-speed flows into large capacity pipes to avoid underutilization of resources [28]. Traffic grooming may require optical-electrical-optical conversion (OEO) to separate connections, which leads to excess power consumption and more delays. In EONs, guard bands between adjacent optical paths avoid the consequences of the imperfect shape of wavelength-selective switch filters when an OFDM signal travels through multiple optical cross-connects (OXCs). Recently, a new traffic grooming scheme has been proposed for EONs [13]. This scheme aggregates traffic requests originating from the same source node and can split this aggregated traffic at intermediate nodes using variable bandwidth switching, but without causing interference.

Fig. 1 (a) illustrates traffic grooming in EONs; Requests 1 and 2 originate at the same source node. Fig. 1b shows the reduction in the use of guard bands.

In survivable optical networks, when any fiber link in the working path fails, the connection is redirected to a backup path. In the traditional form of backup sharing, a single backup path can protect more than one working path, provided they are disjoint. The elasticity of the transponders, i.e., capacity of tuning different rates, allows spectrum overlap [2]. In spectrum overlap, two adjacent lightpaths traversing the same fiber can share the part of the spectrum reserved for backup paths.

Fig. 2 illustrates the spectrum overlap. In this example, the working paths of request 1 is disjoint with the working path of request 2. In case of a failure, connections of that path will use the backup path, which overlaps with the spectrum of the other backup path.

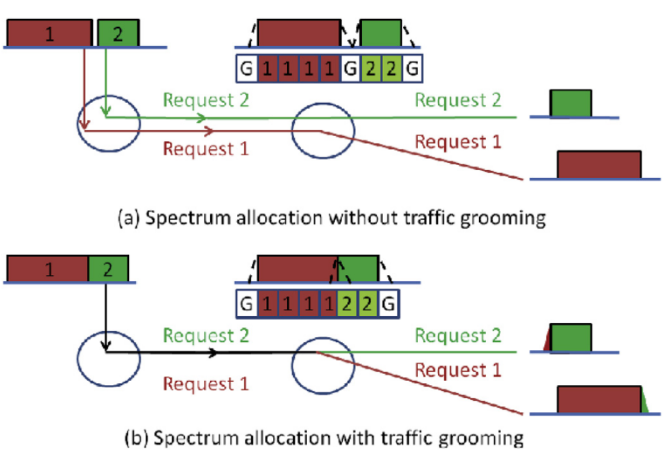


Fig. 1. Traffic grooming in EONs.

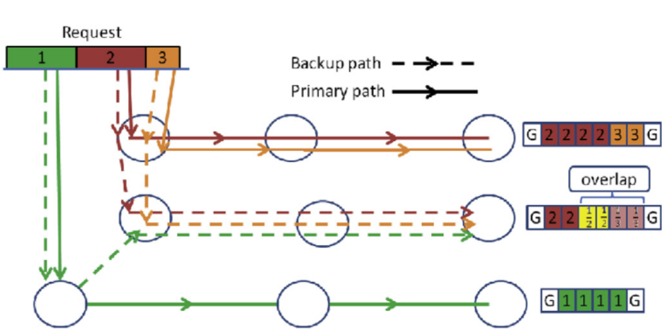


Fig. 2. Overlapped frequency slot.

5. FIPP-Flex-Optimal model (FIPPO)

This section introduces an integer linear optimization formulation called the FIPP-Flex-Optimal model. This optimization model originally proposed in this paper aims at selecting both working and backup paths. It solves the protection problem in EON using FIPP p-cycles. Results derived by the employment of this model are used as benchmark values for comparison with those given by the other algorithms in this paper. The problem of network design with p-cycle is an NP-hard problem, but an ILP requires long runtimes and can thus be solved only for small topologies. In this section, we decompose the problem into two subproblems, one to find the working path and the other to find the backup path (p-cycle). The shortest path is sought for working paths and p-cycles for backup paths both under the constraints of contiguity and continuity for allocation of frequency slots. Using just a shortest path algorithm, such as Dijkstra algorithm would not satisfy the required constraints. The decomposition of the problem into two subproblems allows the extension of the solution for the protection problem in EON to moderate size of networks. The use of a single ILP, on the other hand, would require the use of a large number of resources for dynamic requests.

After finding the working path (Subsection 5.1), the weights of the slots are changed to ∞. When seeking a p-cycle for a backup path (section 5.2), these weight values are considered.

5.1. Shortest path formulation

The following variables are defined to formulate the search for a shortest path:

- r: bandwidth requirement in Gb/s;
- f: source node;
- d: destination node;
- b: The number of frequency slots required to satisfy r;
- $W_{i,j,s}$: The weight of slots in the fiber link, $W_{i,j,s} = \infty$ if the slot s in the link i, j is already allocated;
- $\pi_{i,j,s} \in \{0, 1\}$: a binary variable with a value of 1 if slot s in the link i, j is used; otherwise, it is zero;
- $\alpha_s \in \{0,1\}$: a binary variable with a value of 1 if slot s is used in all links; otherwise, it is zero;
- $\beta_s \in \{0,1\}$: a binary variable with a value of 1 if slot s is the least ordered slot allocated to a lightpath. Otherwise, it is zero;
- $\eta_{i,j} \in \{0,1\}$: a binary variable with a value of 1 if link i, j is used; otherwise, it is zero;

The ILP model to obtain a working path is formulated as following:

$$Min \sum_{i,j,s} W_{i,j,s} \cdot \pi_{i,j,s} \quad (1)$$

Subject to:

$$\sum_j \pi_{i,j,s} - \sum_j \pi_{j,i,s} = \begin{cases} \alpha_s, & \text{if } i = f \\ -\alpha_s, & \text{if } i = d \\ 0, & \text{otherwise} \end{cases} \quad \forall i, s \quad (2)$$

$$\sum_s \pi_{ijs} = b \cdot \eta_{i,j} \quad \forall i, j \quad (3)$$

$$\sum_s \alpha_s = b \quad (4)$$

$$\sum_s \beta_s = 1 \quad (5)$$

$$\alpha_s \le \beta_s + \alpha_{s-1} \quad \forall s > 0 \quad (6)$$

$$\alpha_0 = \beta_0 \tag{7}$$

The objective function (Equation (1)) guides the search for a path with minimum cost. The path should respect the spectrum continuity constraint, which imposes the allocation of the same spectrum for each fiber along the route of a lightpath. Moreover, the slots must be contiguously allocated in the spectrum (the spectrum contiguity constraint).

In this ILP model, we search for b lightpaths, where b represents the number of slots to be allocated, and ensure that the b lightpaths found are continuous. As a result, we obtain a lightpath with b continuous and contiguous slots.

Information on already established paths is given as input to the problem. Constraint 2 uses the traditional way of representing a path in a graph (Kirchhoff equations). This constraint ensures that a set of lightpaths of 1 slot each is found. α_s guarantees the contiguity of slots, i.e., all links use the same slots. Constraint 3 ensures that all lightpaths are established along the same route. For the lightpath to be formed from b lightpaths, these lightpath need to use the same links. This constraint guarantees the use of b slots or none. Constraint 4 defines the capacity constraint so that b slots are chosen in α_s, ensuring that the created lightpath has sufficient capacity. Constraints 5, 6 and 7 guarantee the contiguity of slots. Constraints 5 guarantees the first slot of the set of slots that form the lightpath. Constraints 6 guarantees the continuity considering the least ordered slot with a value of 1 in β_s. Constraints 7 guarantees the continuity when the slot 0 is used.

5.2. p-Cycle formulation

The FIPP p-cycle is a ring formed by two connected disjoint paths, which use the same slot of the spectrum. These two paths have the same ending nodes. The ILP defined next seeks two disjoint paths with the same ending points and using the same slots.

The following variables and constants are defined to formulate an ILP to select p-cycles:

- r: bandwidth requirement in Gb/s;
- f: source node;
- d: destination node;
- b: The number of frequency slots required to satisfy r.
- $W_{i,j,s}$: the weight of slots in the fiber link, $W_{i,j,s} = \infty$ if the slot s in the link i, j is already allocated;
- $\gamma_{i,j} \in \{0, 1\}$: a binary variable with a value of 1 if the slot s in the link i, j is used to form the second (disjoint) path of the p-cycle, the value of this variable is one. Otherwise, it is zero;
- $\alpha_s \in \{0, 1\}$: a binary variable with a value of 1 if the slot s is used in all links, otherwise, it is zero;
- $\beta_s \in \{0, 1\}$: a binary variable with a value of 1 if the slot s is the least ordered slot allocated, otherwise, it is zero;
- $\eta_{i,j} \in \{0, 1\}$: a binary variable with a value of 1 if link i, j is used to form the first (disjoint) path on p-cycle; otherwise, it is zero;
- $\Phi_{i,j} \in \{0, 1\}$: a binary variable with a value of 1 if link i, j is used to form the second (disjoint) path on p-cycle; otherwise, it is zero;

The ILP model to find the p-cycle is formulated as following:

$$Min \sum_{i,j,s} W_{i,j,s} \cdot \chi_{i,j,s} + W_{i,j,s} \cdot \gamma_{i,j,s} \tag{8}$$

Subject to:

$$\sum_j \chi_{i,j,s} - \sum_j \chi_{j,i,s} = \begin{cases} \alpha_s, & \text{if } i = f \\ -\alpha_s, & \text{if } i = d \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

$$\sum_j \gamma_{i,j,s} - \sum_j \gamma_{j,i,s} = \begin{cases} \alpha_s, & \text{if } i = f \\ -\alpha_s, & \text{if } i = d \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

$$\sum_{i,j,s} \gamma_{i,j,s} + \chi_{j,i,s} \le 1 \tag{11}$$

$$\sum_s \pi_{ijs} = b \cdot \eta_{i,j} \quad \forall i,j \tag{12}$$

$$\sum_s \pi_{ijs} = b \cdot \Phi_{i,j} \quad \forall i,j \tag{13}$$

$$\sum_s \alpha_s = b \tag{14}$$

$$\sum_s \beta_s = 1 \tag{15}$$

$$\alpha_s \le \beta_s + \alpha_{s-1} \quad \forall s > 0 \tag{16}$$

$$\alpha_0 = \beta_0 \tag{17}$$

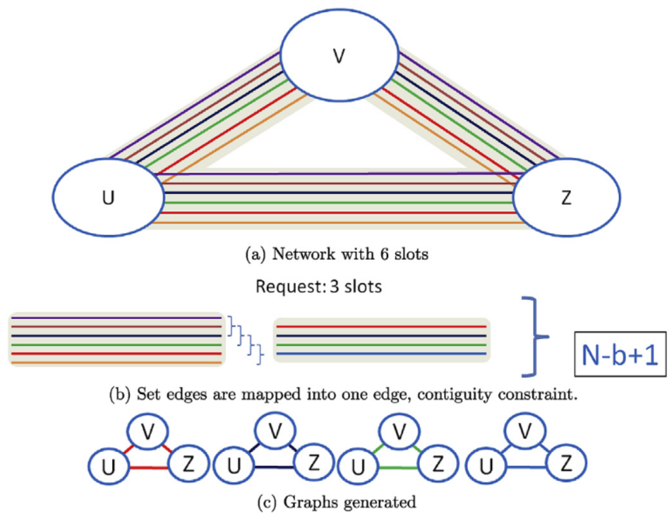
The objective function (Equation (8)) finds the p-cycle between source f and destination d with the minimum cost. A p-cycle is composed by two disjoint paths; the first term of Equation (8) considers the first path for the creation of the p-cycle, while the second term of Equation (8) considers the second path for its creation. Slot continuity is guaranteed by the inclusion of the index s for all variables. Constraints 9 and 10 are the representation of two different paths in a graph. Constraint 11 ensures that the two paths that compose the p-cycle are disjoint. Constraints 12 and 13 ensures that all lightpaths are established along the same route. Constraint 14 defines the capacity constraint, i.e., ensure that b slots are chosen in α_s. Constraints 15 to 17 guarantee the contiguity of slots. Constraints 15 defines the first slot of the set of slots allocated to the p-cycle. Constraints 16 guarantees the continuity considering the first slot with a value of 1 in β_s. Constraints 17 guarantees the continuity when the slot 0 is used.

6. Network modeling

We model the spectrum availability in the network as a labeled multigraph $G(V, E, W)$, composed of a set of nodes V, a set of edges E and a set of edge weight W. The edges connecting two vertices of G represent the N slots in the link connecting two network nodes. $e_{u,v,n}$ denote the edge that represents the nth slot. $R(f, d, r)$ denote a request, where $f, d \in V$ are the source and destination nodes, its bandwidth requirement is r Gb/s, and b denotes the number of frequency slots required to satisfy the bandwidth requirement r.

The original multigraph G (Fig. 3a) is transformed into N-$b+1$ graphs (Fig. 3c) with the edges in these graphs representing a combination of b slots (Fig. 3b). Each edge in these graphs represents a combination of b slots. The nth graph generated is represented by $\tilde{G}_{n,b}(\tilde{V}, \tilde{E}, \tilde{W})$, where $\tilde{E}$ is the set of edges connecting $\{\tilde{u}, \tilde{v}\} \in \tilde{V}$, and $\tilde{W}$ is the set of costs associated with $\tilde{E}$. The edges in $\tilde{E}$ correspond to the mapping of b edges in G starting at the. nth *edge*. Therefore, each graph represents a set of n contiguous slots;

We denote P_n as a chain of $\tilde{G}_n$ such that the source node f is the least ordered node and d is the highest ordered node, i.e., the shortest possible path in all generated graphs. C_n is a chain of $\tilde{G}_n$ such that the nodes f and d are in the chain; Z_n is an established p-cycle containing vertices u and v as well as b edges of the multigraph G;



(a) Network with 6 slots

(b) Set edges are mapped into one edge, contiguity constraint.

(c) Graphs generated

Fig. 3. Multigraph representation of a network spectrum.

7. The RSA-Flex Algorithm

This section presents the routing and spectrum assignment (RSA) algorithm, called RSA-Flex algorithm, which was introduced by the authors in Ref. [5]. The RSA-Flex algorithm is employed by all the other algorithms in this paper. Similar to solutions for the routing and wavelength assignment problem (RWA) in fixed-grid WDM networks, solutions for the routing and spectrum assignment in elastic optical networks are needed to accommodate incoming traffic demands efficiently. The allocation of the same spectrum in each fiber along the route of a lightpath must be guaranteed (the spectrum continuity constraint). Moreover, in elastic optical networks, slots must be contiguously allocated in the spectrum (the spectrum contiguity constraint.) In elastic optical networks, the slot or mini-grid is the unit for spectrum allocation. In these networks, bandwidth demand can be supported by allocating several contiguous slots, thus ensuring that enough spectrum is allocated, which facilitates the support of a variety of bandwidth requirements. The slots are separated by guard bands to cope with the imperfect shape of wavelength selective filters. A small grid granularity (e.g. 3 GHz) has been shown to produce performance equivalent of a gridless network; such gridless optical networks uses the spectrum more efficiently than do WDM networks. Such flexibility makes unnecessary traffic grooming and multipath routing to cope, respectively, with subwavelength and superwavelength bandwidth demands as needed in WDM networks [29]. However, in this paper, we show that the combination of traffic grooming and spectrum overlap in elastic optical networks allows significant gains in spectrum utilization, decreasing, as a consequence, the blocking of requests for connection establishment.

Algorithm 1 details the RSA-Flex algorithm. In this algorithm, Line 1 establishes the set of edges to be mapped onto the $\tilde{G}_{n,b}$ edges, as shown in Section 6. Line 3 solves a shortest path algorithm for the graph $\tilde{G}_{n,b}$ and provides the path and its weight. Line 5 selects the path among the $N\,b+1$ shortest paths that has the lowest weight value. If the weights of all shortest paths are ∞ (Line 6), there is no path in the network that satisfies the request for b slots while observing the contiguity constraint. Therefore, the request has to be blocked (Line 7). Otherwise, the shortest path with the lowest value is chosen and the corresponding edges in the multigraph G have their weights changed to ∞ (Line 9) indicating that these slots were allocated to the newly established lightpath.

Algorithm 1
RSA-Flex.

1: transform the multigraph G into $(N-b+1)$ graphs $\tilde{G}_{n,b}$
2: **for** each graph $\tilde{G}_{n,b}$ **do**

(*continued on next column*)

Algorithm 1 (*continued*)

3: compute the shortest working path to request $R(f,d,r)$ in all $\tilde{G}_{n,b}$
4: **end for**
5: obtain the shortest working path P_n
6: **if** the request $R(f,d,r)$ cannot be satisfied with P_n **then**
7: block the request $R(f,d,r)$
8: **else**
9: set the weight of edges of P_n to ∞
10: **end if**

The RSA-Flex Algorithm executes a shortest path algorithm $N-b$ times and considering the use of the Dijkstra Shortest Path algorithm, the computational complexity of the RSA-Flex is $N\cdot(|V|+|E|)\cdot\log(|V|)$.

8. Protection algorithms

8.1. FIPP-Flex algorithm

The FIPP-Flex algorithm (Algorithm 2) creates a FIPP p-cycle to protect the network. The p-cycle created can have both on-cycle and straddling links. The creation of FIPP p-cycle is realized by finding the shortest disjoint paths in the multigraph which when concatenated form a p-cycle. Such a FIPP p-cycle protects disjoint working paths.

The RSA-Flex algorithm along with the FIPP-Flex algorithm decides on the establishment of lightpaths in an FIPP p-cycle protected network. A lightpath is established if and only if it can be protected by a FIPP p-cycle. Requests for lightpath establishment arrive dynamically and for each request an existing p-cycle is sought to protect the potential lightpath. If no existing p-cycle can protect the primary path, the requested lightpath is not established. The FIPP-Flex algorithm assures a protection path for each established lightpath and protection for single failures is guaranteed.

In Algorithm 2, Line 1 finds a path to establish the request *R(f, d, b)* using the RSA-Flex algorithm. If there is no path available (Line 2) then the request is blocked (Line 3). Otherwise, a backup path should be sought (Line 5). If a p-cycle exists, the lightpath is established (Line 6). Otherwise, a p-cycle to protect the lightpath to be established must be created. Line 9 solves the shortest p-cycle for the graph $\tilde{G}_{n,b}$. Line 11 chooses the shortest p-cycle among the computed p-cycles. If there is no p-cycle available (Line 12) then the request is blocked (Line 13). Otherwise, Line 15 provides the p-cycle and its weight and Line 15 establishes the lightpath as well as the p-cycle to satisfy the request.

The computational complexity to find the shortest cycle is twice that of Dijkstras algorithm, i.e., $2N\cdot(V+E)\log(V)$. The FIPP-Flex algorithm executes a shortest cycle algorithm $N-b$ times and implements the RSA-Flex algorithm. Since the computational complexity of the RSA-Flex algorithm is $N\cdot(|V|+|E|)\cdot\log(|V|)$ and the FIPP-Flex algorithm implements it, the computational complexity of the FIPP-Flex is $N\cdot(|V|+|E|)\cdot\log(|V|)$.

Algorithm 2
FIPP-Flex.

1: obtain P_n and $W(P_n)$by RSA-Flex
2: **if** $R(f,d,r)$ cannot be satisfied with P_n **then**
3: block request $R(f,d,r)$
4: **else**
5: **if** exist a p-cycle $Z_n$to protect r **then**
6: establish request $R(f,d,r)$ as $P_n$and Z_n
7: **else**
8: **for** each graph $\tilde{G}_{n,b}$ **do**
9: compute the shortest p-cycle that contain f and d to satisfy the request $R(f,d,r)$ in all $\tilde{G}_{n,b}$
10: **end for**
11: obtain the shortest p-cycle C_n
12: **if** R can not be satisfied with C_n **then**
13: block request $R(f,d,r)$
14: **else**

(*continued on next page*)

Algorithm 2 (*continued*)

```
15:         establish request R(f, d, r) as P_n and C_n
16:       end if
17:    end if
18: end if
```

8.2. *FIPP-Flex-twofailure algorithm*

In operational networks, there is a non-negligible chance of the simultaneous occurrence of more than a single fault. However, most protection algorithms only consider the occurrence of a single failure. The double protection capability of p-cycle straddling is considered here, and the FIPP-Flex algorithm is extended to FIPP-Flex-twofailure algorithm. The occurrence of two failures is modeled based on the fraction of the network affected by the first failure. The algorithm (FIPP-Flex-twofailure) ensures a totally disjoint protection path for the working path, guaranteeing protection for two simultaneous failures. The FIPP-Flex-twofailure algorithm establishes an off-cycle working path, i.e. the p-cycle is disjoint to the working path. The following replaces Line 5 and 9.

```
5:    if exist a straddling p-cycle Z_n to protect R then
9:          compute the straddling p-cycle C_i that contain f and d to satisfy the
      request R(f, d, r)
```

In the FIPP-Flex-twofailure algorithm, a p-cycle of the off-cycle working P_n path is searched (Line 5). If there is no straddling p-cycle. In Line 9, a straddling p-cycle to protect the lightpath to be established is created. Straddling p-cycles ensure a disjoint path of protection for the working path, thus guaranteeing protection from two simultaneous failures since in straddling p-cycles the working path is off-cycle.

Despite the difference between FIPP-Flex and FIPP-Flex-twofailure the complexity for the two algorithms is the same since both create the p-cycle using the Dikjstra algorithm.

8.3. *FIPPSh-Flex algorithm*

The FIPPSh-Flex algorithm differs from the FIPP-Flex algorithm by accounting for traffic grooming and spectrum overlap in the creation of a p-cycle, thus providing more efficient use of backup resources. The key is that a slot can be shared by more than one p-cycle since the working paths are disjoint. The difference is that the following step is introduced before Line 8:

```
create auxiliaries graplis to G̃_{n,b} considering that the slots used for protection can he
  shared
```

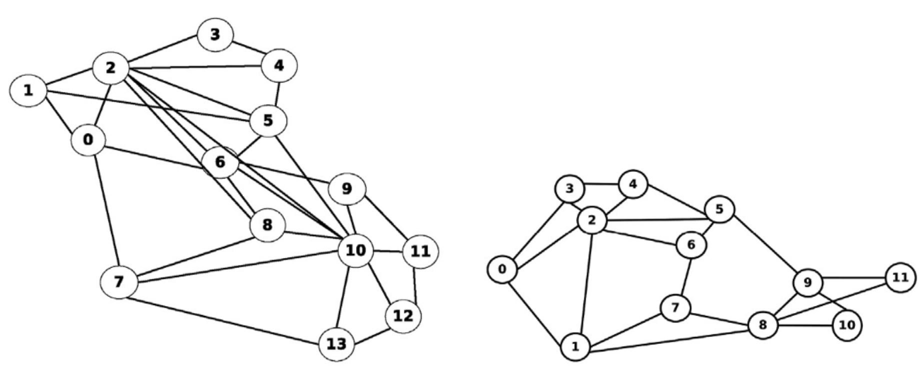
This line establishes a function which produces N − b + 1 graphs, which considers that slots of protection can be shared, since the working paths (P_n) of the new connection are physically disjoint of other working paths that use the slot (spectrum overlap); In summary, FIPP-Flex algorithm assures a backup path for each established lightpath and the protection is guaranteed for single failures. The FIPPSh-Flex and FIPP-Flex-twofailure algorithms extend the FIPP-Flex algorithm. The FIPPSh- Flex algorithm allows traffic grooming on the optical paths as well as spectrum overlap between disjoint backup paths, with the FIPP-Flex-Twofailure algorithm guaranteeing protection for two simultaneous failures. The FIPPSh-Flex algorithm executes the RSA-Flex algorithm, its computational complexity is the same of the complexity of the FIPP-Flex algorithm.

9. Performance evaluation

The Flexgridsim simulator [30] was employed for comparison of the effectiveness of the algorithms described in this paper. For each simulation, 100,000 requests were generated and simulations for each algorithm used the same set of seeds. The load is increased in steps of 25 erlangs. The modulation format BPSK was used with 1 bit per symbol. This modulation format avoids the need of using regenerators for the regeneration of signals. By using BPSK, the lowest transmission rate is achieved when compared to the transmission rates given by other modulation formats. In this way, to satisfy a bandwidth demand, the highest number of slots needs to be allocated when compared to the number of slots required when other modulation levels are employed. This gives a worst case condition for spectrum allocation. Any best performing results given by a p-cycle scheme can potentially be improved if adaptive modulation is employed.

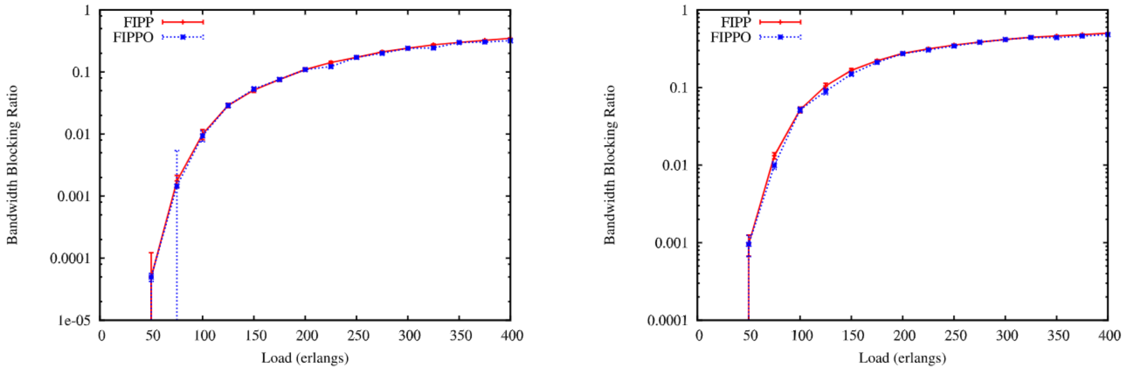
Each simulation run involved three types of connection requests: 20 Gbps, 60 Gbps, 100 Gbps. Confidence intervals with 95% confidence level were generated. The Italy [31] (Fig. 4a) and the CESNET [32] (Fig. 4b) topologies were used. The Italy topology has 14 nodes and 31 links whereas the CESNET topology has 12 nodes and 21 links. In the simulated network, the spectrum was divided into 240 slots of 12,5 GHz each. The mean arrival rate and the mean holding time are adjusted to simulate the desired load in erlangs. The algorithms were evaluated for different metrics: bandwidth blocking ratio, fragmentation ratio, Jain fairness index [33] and average number of hops for working and backup paths.

Fig. 5 shows the bandwidth blocking ratio (BBR) which is the fraction of the total bandwidth request not provided in relation to the total bandwidth requested as a function of the network load for the Italy and CESNET topologies. The curves labeled FIPP indicate the protection provided by the FIPP-Flex and RSA-Flex algorithms, while the curves labeled "FIPPO" plot results for the network using the FIPP-Flex-Optimal algorithm. FIPPO results are derived by solving the ILP. The FIPPO algorithm was used in this paper to evaluate the precision of the three proposed algorithms. The solver CPLEX 12.06 was used to solve the



(a) Italy Topology (b) CESNET Topology

Fig. 4. Topologies.



(a) Italy Topology (b) CESNET Topology

Fig. 5. Bandwidth blocking ratio as a function of the load.

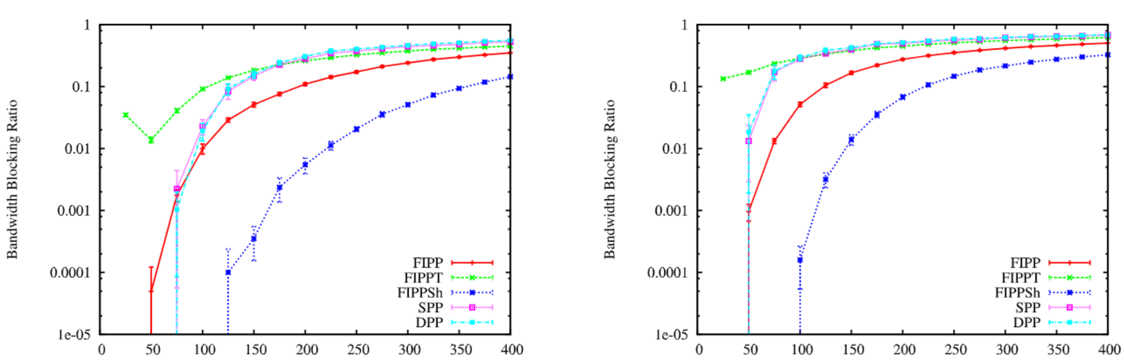
proposed ILP model on a PC equipped with a 3.4 GHz CPU and 30 GB RAM.

The FIPP-Flex and FIPPO algorithms start blocking requests under 50 erlangs. The BBR values produced by the two algorithms are very similar. Results derived using the FIPP-Flex algorithm are very similar to those given by the ILP. The error in BBR estimation is less than 1%. Moreover, the FIPP algorithm requires fewer resources than does the FIPPO, since the latter needs more memory to compute feasible solutions. Since the results given by the FIPP-Flex algorithm are quite precise, they will be used for comparison with the other proposed algorithms. The results obtained from the ILP model will not be shown in the following examples.

Next, results produced by the proposed algorithms will be compared to those given by the survivable-FWDM algorithm [3] and those produced by the SPP- OFDM-Aggressive algorithm [1]; since both are algorithms widely used in the literature. The SPP-OFDM-Aggressive algorithm provides SBPP protection, and employs a k-shortest path algorithm and the First-Fit policy to allocate subcarriers. The subcarriers allocated to the working path are removed from the auxiliary graph and the k-shortest path is executed to determine the backup paths. The survivable- FWDM algorithm constructs an auxiliary graph in which edges represent available slots. It finds k pairs of disjoint paths and chooses one pair to be the working path and another to be the backup paths. In the figures, the curves labeled “DPP” show the results for networks using the survivable-FWDM algorithm [3], while curves labeled “SPP” display the results using the SPP-OFDM-Aggressive algorithm [1]. The curves labeled “FIPP”, “FIPPSh” and “FIPPT” plot results for the FIPP- Flex, FIPPSh-Flex and FIPP-Flex-Twofailure algorithms, respectively. All these algorithms use the RSA-Flex algorithm.

Fig. 6 plots the bandwidth blocking ratio (BBR) as a function of the network load for the Italy and CESNET topologies. For the Italy topology (Fig. 6a), the FIPPSh algorithm starts to block requests only under 125 erlangs, while the FIPP and FIPPT algorithms start blocking requests under 25 and 50 erlangs, respectively. The DPP and SPP algorithms start blocking requests under 75 erlangs. The FIPPT algorithm produces the highest BBR value, because it reserves more bandwidth to protect against two failures, leaving less bandwidth for incoming requests. Under high loads of 175 erlangs, the BBR produced by DPP and SPP are the highest ones, since these algorithms share fewer backup paths than do the algorithms employing p-cycle; and therefore FIPP p-cycles protect the on-cycle and straddling paths, thus increasing their ability to share the spectrum. The BBR values produced by FIPP are always lower than those produced by FIPPT, the BBR values produced by FIPPSh are always the lowest one, due to the employment of traffic grooming and spectrum overlap.

For the CESNET topology (Fig. 6b), the FIPPSh algorithm also produces the lowest blocking ratios values, and it starts to block requests under 100 erlangs, while the SPP and DPP algorithms started blocking requests under 50 erlangs. The FIPPT algorithm started blocking requests under loads as low as 25 erlangs. The high BBR values produced by the FIPPT algorithm are due to the cost of protection against two failures. Under high loads of 125 erlangs, the BBR produced by the DPP and SPP are higher than those produced by the other algorithms, since p-cycles share paths and consequently reserve fewer resources for protection. Moreover, the DPP and SPP do not provide pre-connected backup paths, and consequently, restoration takes longer. The BBR values produced by the FIPP algorithm were always lower than the value produced by the FIPPT. The performance of the FIPPT algorithm is affected by the low



(a) Italy Topology (b) CESNET Topology

Fig. 6. Bandwidth blocking ratio as a function of the load.

connectivities of the nodes and, it consequently started blocking requests under low load. The FIPPSh-Flex combines the advantages of sharing, traffic grooming, and spectrum overlap, thus producing less blocking.

In elastic optical networks, the existence of connections requiring a variable number of slots leads to the fragmentation of the spectrum available into small noncontinuous slot chunks, which makes the allocation of new connections difficult, especially for those demanding large bandwidth. The problem of fragmentation is even more striking in dynamic scenarios, in which connections are frequently established and torn-down. The fragmentation ratio translates the chances for requests of different types to be rejected due to this spectrum fragmentation.

Fragmentation is generated given the degree which the spectrum is fragmented from the establishment and the tear-down of paths. The fragmentation ratio compares the maximum number of contiguous slots available to the number of slots available on the link. The fragmentation ratio is given by:

$$FR = \frac{MaximumNumberOfContiguousSlotsAvailable}{NumberOfSlotsAvailable} \quad (18)$$

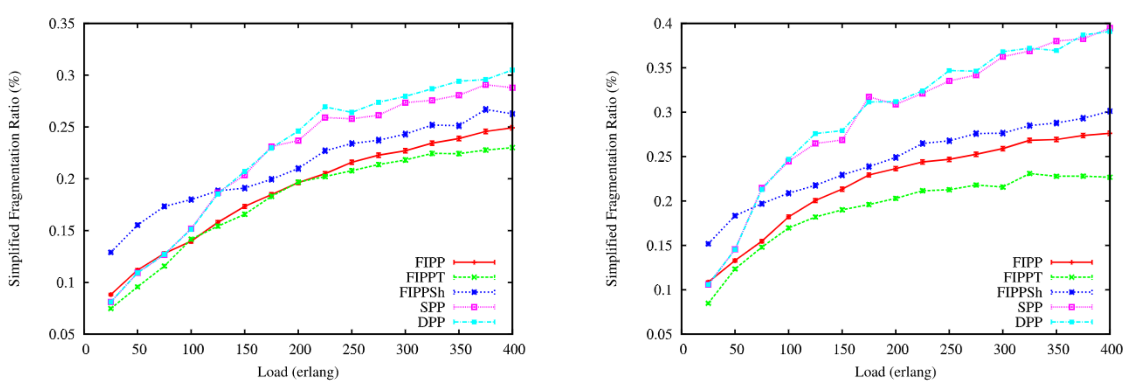
Fig. 7 shows the fragmentation ratio as a function of the load for the Italy and CESNET topologies. For the Italy topology (Fig. 7a), the fragmentation ratio shows a trend similar to that of the bandwidth blocking ratio, which was expected since the fragmentation ratio influences the blocking of requests.

For the SPP and DPP algorithms, the difference between the fragmentation ratios arises only for loads higher than 100 erlangs. These algorithms produce a fragmentation ratio 14% higher than the other algorithms that use p-cycles, so that a backup path can protect multiple paths since p-cycles protect all end-node paths on the cycle; this generates less removal and creation of backup paths and thus less fragmentation of the spectrum.

For the CESNET topology (Fig. 7b), the fragmentation ratios produced by the SPP and DPP algorithms are the highest ones. This is due to the promotion of greater sharing, thus generating a smaller number of disconnected backup paths, and reducing the available spectrum that cannot be used by incoming requests. The FIPPT algorithm produces a fragmentation ratio of 5% lower than that given by the FIPP algorithm, mainly under high loads, as consequence of the blocking arising from the low number of alternative paths. The combination of spectrum overlap and traffic grooming in the FIPPSh algorithm evinces the advantage of such a combination in contrast to the performance of the other algorithms.

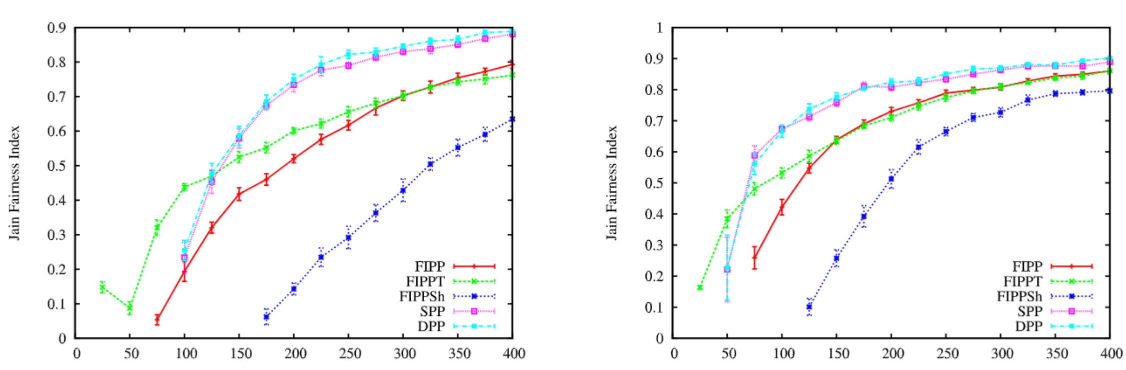
Fig. 8 displays the Jain Fairness Index (JFI) [33] of the BBR used by different source-destination pairs for the Italy and CESNET topologies. The JFI value shows how the blocking ratio is distributed between the source-destination pairs in the network. Under high loads, the BPP and SBPP algorithms which produce greater BBR values have high Jain index values, distributing the blocking requests more evenly between the source and destination pairs. The FIPP, FIPPSh and FIPPT algorithms have low Jain index values as a result of the low BBR values yielded.

For the Italy topology (Fig. 8a), the SPP and DPP algorithms produce similar Jain Index values regardless of the network load although this does not happen with the other algorithms. The high Jain index values of the SPP and DPP algorithms are due to the high blocking produced which affects uniformly all source- destination pairs. There is not much difference between the fragmentation ratios produced by the FIPP and FIPPT algorithms, the difference arises only under heavy load. Under heavy loads, the SPP and DPP algorithms produce Jain index 12% higher than



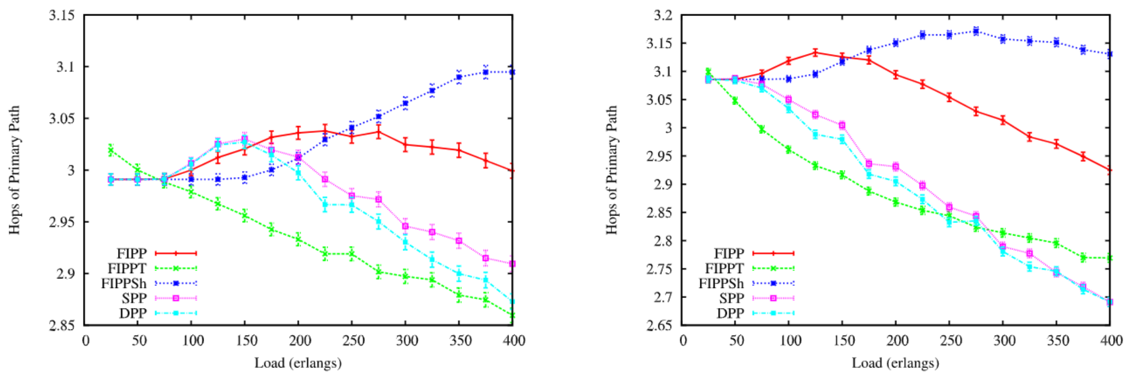
(a) Italy Topology (b) CESNET Topology

Fig. 7. Fragmentation ratio as a function of the load.



(a) Italy Topology (b) CESNET Topology

Fig. 8. Jain fairness index as a function of the load.



(a) Italy Topology (b) CESNET Topology

Fig. 9. Average number of hops of working paths as a function of the load.

those arising from the algorithm using p-cycle.

For the CESNET topology (Fig. 8b), the SPP and DPP algorithms also have the highest Jain index values as a function of high blocking produced which affect uniformly on all source-destination pairs. Under high loads, the FIPPT algorithm produces lower Jain Index values than do SPP and DPP since various source- destination pairs do not suffer blocking. For both topologies, the FIPPSh algorithm produces low Jain Index of fairness since several source destination pairs do not suffer blocking, especially under low loads, which leads to a greater disparity in BBR values.

Fig. 9 shows the average number of hops in the lightpath allocated to working paths. The higher the load, the smaller the average number of hops allocated per working path. This happens because, under high loads, only short paths can be established since the spectrum is already allocated.

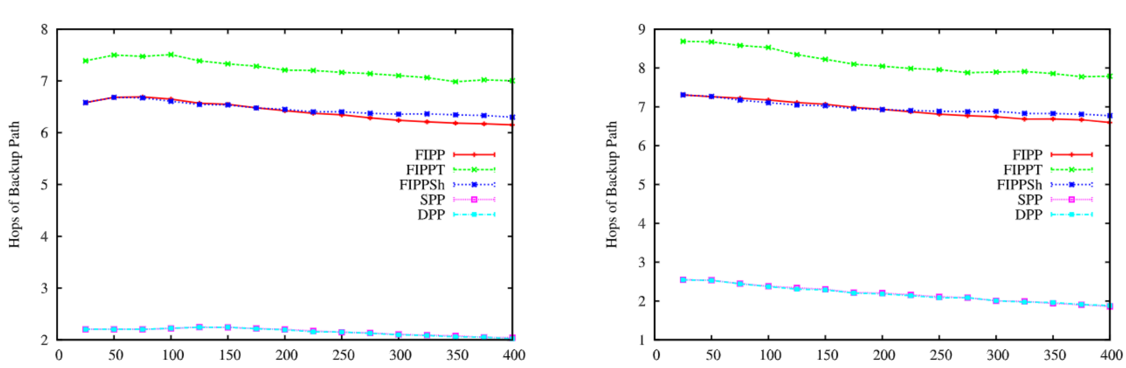
For the Italy topology (Fig. 9a), the capacity of path allocation is reduced significantly for the FIPP, FIPPT, DPP and SPP algorithms as blocking increases under high loads. The FIPPSh, however, maintains the capacity to establish paths of different lengths, as can be seen by the almost constant average path length. This happens because the network is not saturated as a result of the use of traffic grooming and shared spectrum overlap schemes.

For the CESNET topology (Fig. 9b), as both the load and the BBR increase (as a consequence of the decrease of the average number of hops allocated per working path), only short paths can be allocated. The blocking produced in this topology affects the capacity of establishing paths with arbitrary lengths, although with the FIPPSh algorithm, this capacity is not much affected.

Fig. 10 shows the average number of hops in the allocated lightpath of backup paths for the Italy and CESNET topologies. The algorithms using p-cycle, required a higher number of hops for the backup path. However, the sharing of p-cycles paths makes better use of the network resources, since a p-cycle protects a greater number of working paths. For both topologies (Fig. 10a and b), the FIPPT algorithms lead to the highest average number of hops in the allocated lightpath of backup paths, since two alternatives path are allocated for protection in case of two simultaneous failures. The SPP and DPP algorithms have the lowest average number of hops in these lightpaths because they do not use FIPP p-cycles, whereas the FIPP p-cycle algorithms need two paths for its creation. This feature, however, is what makes the FIPP p-cycle algorithm capable of protecting for a higher number of paths.

10. Conclusions

This paper presents algorithms to support the establishment of lightpaths in elastic optical networks protected by FIPP p-cycles. The p-cycle method benefits from the fast restoration of ring-like protection and high capacity efficiency of mesh protection. The algorithms were evaluated for different topologies and loads. The FIPP-Flex, FIPPSh-Flex and FIPP-Flex-Optimal algorithms provide 100% protection for single failures, while the FIPP-Flex-Twofailure algorithm provides 100% protection for two simultaneous failures. Protection against two failures requires the creation of three disjoint paths which affects significantly the bandwidth blocking ratio, increasing up to 30% in relation to a scenario with a single failure. Results indicate that the overhead demanded by the FIPP-Flex-Twofailure algorithm is, however, quite acceptable for networks with high node connectivities (Italy), although not very attractive for networks with low node connectivities (CESNET). The results are in



(a) Italy Topology (b) CESNET Topology

Fig. 10. Average number of hops of backup as a function of the load.

line with those derived for other topologies (NSF and USA) [6]. Moreover, when compared to the SPP-OFDM-Aggressive and survivable-FWDM algorithms, the FIPP-Flex algorithm produces more attractive results, since it employs a pre-connected path scheme. Algorithms using overlapping spectra present more attractive results for both topologies than do the other algorithms. By assuming the BPSK modulation format, the highest number of slots for a specific bandwidth demand is always allocated. Therefore, results for p-cycle schemes in this paper are lower bound to the results that can be achieved if adaptive modulation is employed. As future work, different modulation schemes and physical impairments will be considered in the RSA-Flex algorithm to explore the potential advantages of the proposed algorithms.

Conflict of interest

None.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.osn.2019.100535.

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